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The use of edge gradient analysis on chrome and emulsion photomasks to determine modulation transfer functions

Marcy E. Levin

THE USE OF EDGE GRADIENT ANALYSIS ON CHROME AND EMULSION PHOTOMASKS TO DETERMINE MODULATION TRANSFER FUNCTIONS

by

Marcy E. Levin

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

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Date April 19, 1985

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ABSTRACT

Using edge gradient analysis on chrome and emulsion photomasks to determine the modulation transfer function of a mask making system proved to be limited by the method in which the edge gradients were observed. Scanning electron micrographs were taken of the chrome and emulsion edges on various masks, and results showed that chrome photomasks exhibit steeper gradients and better edge acuity than emulsion images. However, due to the ratio of line size to gradient size on each of the types of masks, it was decided that the gradient would not make a significant contribution to modulation loss in the image.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

As the microelectronic industry places greater demands on packing more circuit devices on a single chip, the precise tooling of photomasks is critical. Photomasks are an important part of the making of the integrated circuit (IC), so poor image resolution and mask quality can severely limit IC yields.

Edge gradient analysis on a photomask may be an important consideration as the lines and spaces of a photomask approach the submicron level. In a projection printing system, diffraction limits the maximum resolving power of a system.[1] Lines and spaces on a photomask act as a diffraction grating when illuminated with monochromatic light. According to Figure 1 below, the diffracted illumination results in the projected image showing gradual transitions from light to dark. The sharp edges of the mask have been blurred.

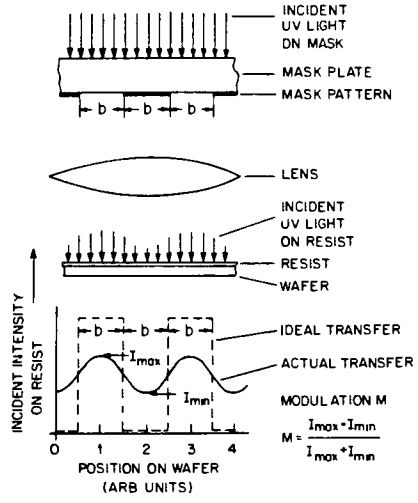

Figure 1. Projection Printing

As the size of the lines approach 1 micron, the image of the opaque lines would contain more light. Therefore the modulation in the image plane would be reduced.

In contact printing, the primary resolution limitation is the diffracted light at the edge of an opaque line on the mask (as previously described). From the figure below, one can see how the image of a perfectly straight edge can become blurred and diffused at the image surface by contact printing.

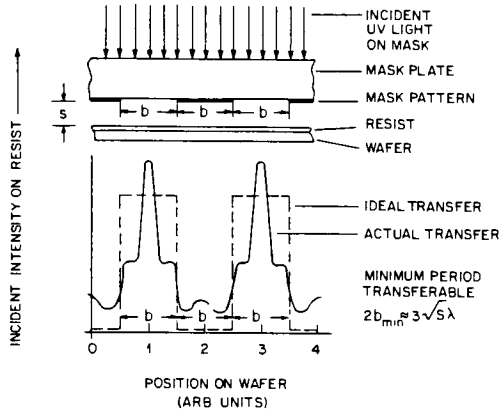

Figure 2. Contact Printing

Contact printing is the most accurate method of reproducing an object in lithography, but if contamination is between the two surfaces in contact, damage will occur to both the master and the contact print. Lack of flatness of either plate will also cause major distortions and thereby degrade the resolution for this technique.

In optical lithography, a number of factors are

introduced by the system to contribute to the degradation of image contrast. A study was performed by Arden, Klose, and Krause[2] on improving contrast in 10:1 projection optics, by the use of antireflective coatings on the mask and wafer. It was concluded that scattering of light from reflections between reticle and projection lens, and reflections between wafer and projection lens, caused contrast degradation of the image. The method used to measure the image contrast was the application of the photoresist as the threshold detector. This method seemed quite suitable for characterizing the performance of a projection lens. However, if one has a final image which was produced by a series of exposures, step and repeat imaging, and processing, the performance of the projection lens is just one factor contributing to the total image degradation. A chrome or emulsion work plate is produced by a series of these steps, and this process was evaluated by the use of edge gradient analysis on the chrome and emulsion work plate.

In the same experiment[3], it was also concluded that a bright field mask (dark features with light surrounding) with an antireflective coating improved image contrast "up to 10%." An antireflective coating for a chrome mask is usually a 200 Å layer of chrome oxide on top of the chrome layer. Without the antireflective layer underneath the photoresist, standing waves are formed in the resist.[4] The standing waves produce edge fringes or contours on the wall of the resist profile. These variations limit the resolution and linewidth control of the photoresist.[5] The variation in the photoresist

linewidths may produce variations in the chrome linewidths, unless the etching procedure is altered to compensate for the changes in resist linewidths.

A. Etching

Chemical etching methods have been more widely used for etching chrome and chrome oxide layers than dry or plasma etching. According to Mucha and Hess [6], the acidic properties of most etchants cause the resist to lose its adhesion to the surface below it. Once again, this will alter pattern dimensions and prevent linewidth control. Another result of chemical etching is that as it etches downward, it etches laterally at an equal rate. This produces an isotropic profile of the chrome mask walls. To obtain an anisotropic etch, a plasma or dry etch process is required. Chrome masks for this evaluation have been etched with an acidic etchant. It is evident that there are processing factors which alter the image quality of the mask, so the quality of the mask pattern is critical for the fabrication of the final IC device.

B. Mask Fabrication

A current method of transferring a circuit design onto a photomask is by the use of photo-optical equipment. The method used to fabricate a work plate for this investigation

begins by using a computer aided design (CAD) system. From this, a single circuit layer is stored on magnetic tape and a pattern generator is used to expose an emulsion and chrome photoplate. This reticle is then placed in a 10:1 automatic reduction reticle stepper, which produces a mask containing the same circuit design, but reduced to one-tenth its original size and stepped across the entire mask. The mask is then contact printed using a photomask contact printer . This chrome or emulsion contact print is sometimes referred to as the "work plate", for it is this mask which is commonly used to proximity print or contact print on to the wafer. Between each of these steps on the chrome plates, the photoresist is the light sensitive medium and it acts as a mask while the chrome is chemically etched.

C. Image Degradation

This total mask making system can be described as a sequence of convolutions. Each different process in the system described above has particular spread function, and all of these steps combined will tend to reduce the resolution of the final image. Beginning with the exposure to produce a reticle, the scattering of the incident photons at a single point describes the spread function of the reduction lens of the photorepeater (it describes the spread of a point of light). The convolution of the image with the spread function of the processing chemistry may reduce the

resolution of the image even more. The image is then contact printed to a chrome or emulsion blank and developed to produce the final work plate. In other words, the image is considered the convolution of the object with the line spread function of the system. It is desired to predict what the final image distribution will be and to see how the modulation is altered from object (reticle) to image (work plate) under the specific parameters of this mask making process.

D. Chrome Photoplates

The compositions of photoplates used in the microelectronic industry are varied. Common photomask materials include bright or antireflective chromium sputtered on a substrate material such as soda-lime glass or quartz. A layer of optical photoresist is applied on top of the chrome, acting as a mask to the chrome layer. The usual thickness of the chrome layer is 1000 Å and antireflective chrome plates usually contain a top layer of chrome oxide. Photoplates donated by Gould/American Microsystems, Inc. have a soda-lime glass substrate, and were coated with 5000 Å of AZ-1350J positive photoresist. All testing was done with the anti-reflective chrome plates. These plates contain approximately a 200 Å of chrome-oxide on the chrome surface.

E. Emulsion Photoplates

Despite the change toward hard - surface photomasks such as chromium (as previously discussed), emulsion masks are still used throughout the semiconductor industry. An extensive study was performed by Angel and Johnson[7] on the state of emulsion plates used in the industry. It was found that the control of critical dimensions can be best achieved if the time between exposure and development of the emulsion is less than one hour. Agfa-Gevaert High Definition plates, for example, exhibited low - defect counts in the one to two micron range. The mask makers primary concerns are adequate density and contrast, image quality, dimensional accuracy and useful resolution. It was found by Altman[8] that the density of the emulsion images depend on their size. He claimed that smaller images will be less dense than larger images under the same exposure conditions. This change in density on a mask would represent a contrast loss from the mask to the image. Finer geometries would not be resolvable on the projected image if there were changes in density on the mask.

The advantages of emulsion masks are that they are inexpensive, and, as a master reticle, the high speed of the photographic emulsion is an advantage in getting throughput with a pattern generator.[9] The high contrast silver halide emulsions, however, may limit the resolution of the mask, and the softness of the emulsion limits the mask life. The

emulsion mask as a master is an inexpensive way of projecting images on to wafers, but the reduction in contrast at higher spatial frequencies is an important consideration if small geometries are to be required. Image degradation in the emulsion masks is due to the scattering of the exposing light in the emulsion, and the MTF generated from the edge profiles in this study will indicate how much contrast of the image will be lost as the frequency of the geometries increases.

It is desirable to find out how well a mask making system performs and to predict what the objects will look like when imaged by the system. A quantitative way of specifying the performance is needed. With a complex series of optical components in the system, from photorepeating to contact printing, it is difficult to predict what the final image would look like.

F. Modulation Transfer Function

"Modulation transfer function (MTF) describes the ability of a lens or system to transfer object contrast to the image, as a function of spatial frequency."[10] The concept of modulation transfer function (MTF) is used to describe and predict resolution capabilities of projection printers and photorepeaters. The MTF describes the ability of transferring an image with respect to contrast or modulation. MTF is the

ratio of image modulation to object modulation and is a function of spatial frequency. Modulation is defined as;

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

where I_{max} is the intensity through the clear line and I_{min} is the intensity through the opaque line. For a "perfect" mask, the modulation would be one, but due to gradients along the edge of the lines, modulation would be less than one. The modulation would decrease as it approaches a certain cut-off frequency, and then it would reduce to zero.

Methods exist to determine the transfer function from edge gradients. A method proposed by Scott, Scott and Shack[11] involves sampling an edge trace around the midpoint of the edge response curve. The square wave modulation is computed by a relatively simple sum and difference calculation and the sine wave response (MTF) is determined from the square wave modulation and a harmonic component correction.[12] However, the accuracy of this procedure is limited by the aspects of the device used to make the edge trace and by graphical techniques.

A second method used to derive the transfer function is similar to the previous method, but here the fourier transform of the line spread function yields the sine response function.[13] The transfer function (by Tatian's method) is expressed as a trigonometric series whose

coefficients are proportional to the sampled values of the edge response curve.[14] Ewbank stated in his thesis[15] that Tatian's method of edge gradient analysis was used to obtain MTF(f)s of edge scans because it proved easier to use, and it proved to be less influenced by noise. For these reasons, the modulation transfer function curves for the chrome and emulsion masks will be obtained in this study using Tatian's method.

II. EXPERIMENTAL

Chrome and emulsion photoplates were provided by Gould/American Microsystems Inc., along with emulsion and chrome resolution target reticles, and chrome workplates with a stepped resolution target pattern. Lab facilities for research were provided by the Microelectronic Engineering Department at RIT, and scanning electron microscopy work was provided by Eastman Kodak Company Research Labs. Equipment used to fabricate work plates was located in the lab facilities at RIT, and equipment included GCA/MANN 1795 photorepeaters, a GCA/MANN Type 2300 contact printer, Cambridge scanning electron microscope, and a Unitron TMS filar measuring system.

In order to fabricate high quality chrome and emulsion photomasks in the Microelectronic Engineering lab, several processing parameters had to be determined.

The first step was to generate a focus series using the GCA/MANN 1795 photorepeater (xenon source) with the 4 sq inch and 5 sq inch emulsion photoplates. The reduction lens (10:1) is a 28mm wide field lens corrected for a wavelength of 546 nm. Development for the emulsion master had to be determined as well. Three high contrast developers were investigated - Kodak High Resolution Plate Developer, Kodak D-19, and Kodak D-8 developer. Development times were varied to obtain high

contrast emulsion images. The plates were evaluated in terms of linewidth accuracy, sharp edges, highest resolution, and high contrast and density. Measurements of the 5 micron lines were used as the "standard" and were measured in the center of the plate and at an upper and lower corner. The Unitron filar measuring system was used, and there was a +/- 0.5 micron variation in repeating linewidth measurements.

The emulsion reticle which was imaged on to the master is composed of a bright field/dark field pattern with linewidths ranging from 500 to 5 micrometers. There is also a checkerboard pattern at every change in linewidth to note the effect of "rounding" at corners. The substrate of the reticle is a soda-lime glass material. An illustration of the mask is given below.

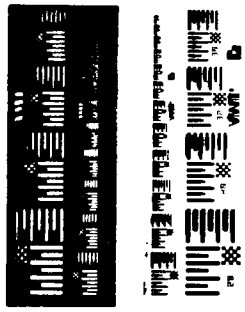

Figure 3. AMI/RIT Test Target

After completing the photorepeating procedures to produce an emulsion master, it was necessary to optimize the processing characteristics of contact printing. The GCA/MANN type 2300 contact printer is equipped with a mercury arc source with 2 broad band pass filters for exposing emulsion or photoresist. The irradiance of the source at an open gate exposure was measured in several locations to determine if there was any variation in irradiance across the plane of exposure. A soda-lime glass plate was then placed on the master chuck frame and irradiance was again measured. This was to note how much irradiance the glass transmitted. Exposure times were varied - ranging from 6 seconds to 10 seconds. The time for evacuation of the air between the plates for a hard contact had also to be determined (pump down time). Using the recommended pump down time as a reference point, (from the contact printing manual) it was possible to determine a pump-down time. Linewidths of 5.0 microns were measured throughout the testing, and the contact prints were also evaluated in terms of resolution and high contrast.

Once establishing the emulsion process for fabricating work plates, it was necessary to repeat the same tests except with photoresist.

The GCA/MANN model 1795 with a mercury arc source was used to fabricate the chrome masters. The photorepeater consisted of a Zeiss 28mm (10:1) reduction lens corrected for

aberration at 436 nm. The reticle that was used for photorepeating was identical to the emulsion target except that it was a bright and dark field chrome mask.

The first step was to determine the focus with the 5 sq inch chrome plates. Large increments of focus were used until it was possible to narrow down the change in focus to 5 X 10^{-4} inch. An exposure time/focus matrix for the chrome plates was generated using the photorepeater. It was possible to optimize focusing of the reticle to within 5 X10^{-6} inch. The irradiance was measured as 1.8 mw/sq cm at the image plane.

The optimum focus/exposure time combination was determined after developing the AZ-1350J positive photoresist in Kodak Micro Positive Resist Developer 809 for 45 seconds (20^{o} +/- 5^{o} C) by measuring the standard linewidths across the plate. It was important to achieve the correct sizes of the photoresist lines and high resolution because the photoresist is a mask to the underlying chrome layer. It is not desirable to over or under etch the chrome for the correct linewidths.

The etchant used for the chrome layer was Chromium Etchant Type 1020 (Transene Company). Etch times were varied from 45 to 60 seconds to optimize linewidths and to assess the overall image quality. The photoresist was then stripped off after etching, using acetone.

Using the chrome mask, contact printing produced the chrome work plate. It was necessary to determine the

pump-down time and exposure for the plates in contact. It was also necessary to cut down the 5 sq inch chrome master and blanks so they would fit in the chuck of the contact printer.

All of the chrome and emulsion plates were then ready to be analyzed using the scanning electron microscope. Because the thickness of the chrome and emulsion was 0.1 microns and 4 microns respectively, it was impossible to view the gradients using the optical equipment at RIT. The samples were sent to Eastman Kodak Company, and were cut into 1 sq inch pieces suitable for SEM analysis. Gold was sputtered on the surface of the samples (125 Å), and micrographs were taken of the 5 micron linewidths.

Cross-sections of the samples were attempted using the Cambridge SEM located in the Microelectronic Engineering lab. However, this piece of equipment did not have the capability to resolve such small step heights. Different sample pieces were used and approximately 200 Å of gold was sputtered on the top and side of the samples. Samples were mounted flat as well as on an edge to resolve the edge profiles.

Software for the determination of the MTF from a sampled edge was developed (see Appendix).

III. RESULTS

A. Characterizing the Emulsion Master Process

The variables of the process and the processing results for fabricating the emulsion masters using the GCA/MANN 1795 photorepeater (xenon source) are outlined below. The emulsion plates used were IMTEC HRP Emulsion Plates (4 x 4 sq in.). Development was by tray processing, followed by a 30 second stop, 4 minutes in fixer, and a 10 minute DI rinse.

Table 1. Process for Emulsion Master

VARIABLES	OPTIMUM PROCESS
FOCUS - 4 sq in plates - 5 sq in plates	 0.0715 inch 0.07425 inch
FLASH INTENSITY	med 10 (relative)
DEVELOPMENT	Kodak Developer D-19 (undil),20°C, tray processing, 8.0 min.

B. Characterizing Chrome Master Process

Chrome masters were fabricated on the GCA/MANN photorepeater using a mercury arc source. Irradiance on the

sample was 1.8 mw/sq cm, and the exposure time for the photoresist was 15 seconds. Photoresist and chrome lines were measured in in the same locations of the plate - at the center and at four corners near the middle point. All wet processing was done by tray, using continuous agitation.

Table 2. Process for Chrome Master

VARIABLES	OPTIMUM PROCESS
EXPOSURE	27.0 mj/sq cm
FOCUS - 5 sq in. plates	0.11925 in.
PHOTORESIST DEVELOPMENT	Kodak Micro Positive Resist Developer 809, (1:1), 20° C, 45 sec.
ETCH	Chromium Etchant Type 1020, Transene Company, 20° C, 60 sec.

C. Linewidths

Lines and spaces of 5.0 microns were measured on the chrome and emulsion masters using the Unitron TMS filar microscope. The repeatabilty of measuring one linewidth was determined to be 0.502 microns (n=21). A 95% confidence interval was placed around the mean to assure that the method used to obtain this interval is 95% reliable.16

Table 3. Linewidths on Masters

MASTER	AVG. LINEWIDTH (microns)	95% CONFIDENCE INTERVAL (microns)
Emulsion	5.19	+/- 0.106 (n=52)
Chrome	5.17	+/- 0.062 (n=64)

D. Contact Printing

Exposure times and pump down times for the contact printer were varied. Air pressure was set constant at 30 psi, and the system pressure was 8 psi. The irradiance measured at the master chuck frame 0.63 mw/sq cm. The photoresist line measurements were taken after the chrome contact plate was developed. After this plate was etched and stripped, chrome lines were measured.

Table 4. Process for Contact Printing

	Pump-Down Time (sec)	Exposure (mj/sq cm)	Linewidths + 95% Conf. Intervals
Emulsion	20	3.90	5.22 +/- 0.163 um
		4.55	4.80 +/- 0.427 um
		5.20	4.83 +/- 0.101 um
		6.50	5.20 +/- 0.586 um
Photoresist	20	7.80	5.29 +/- 0.205 um
		9.75	5.30 +/- 0.121 um
Chrome	20	7.80	5.18 +/- 0.316 um
		9.75	5.51 +/- 0.363 um

E. Scanning Electron Micrographs (SEMs)

On the following pages are the micrographs of 5.0 micron lines (unless indicated otherwise) of the various samples. Approximately 125 Å of gold was sputtered on the samples. Significant differences of edge gradients can be seen between the chrome and emulsion samples.

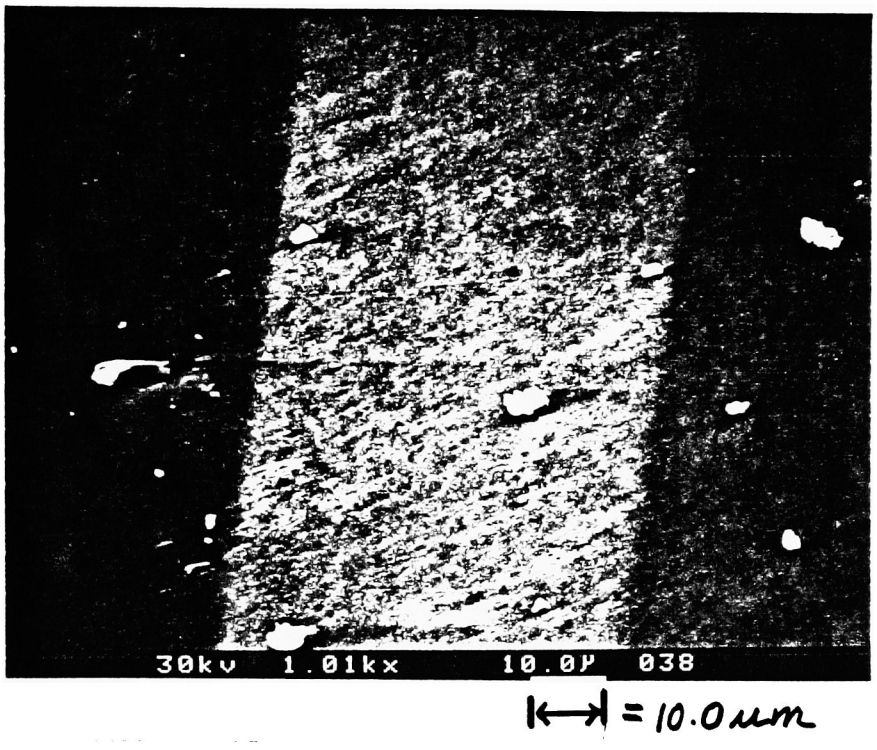

Figure 4. EMULSION RETICLE (50 micron line)

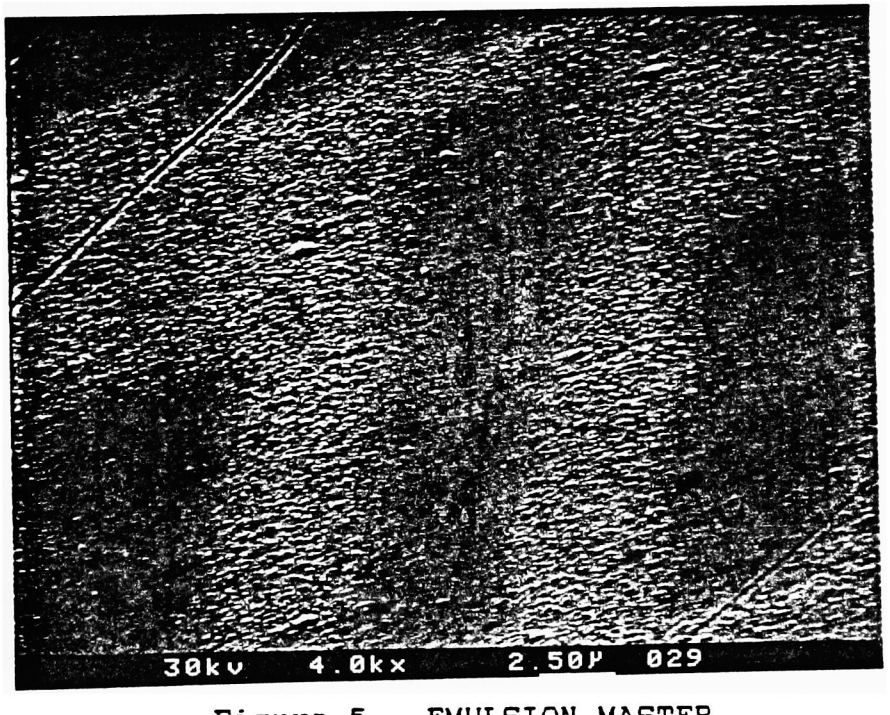

Figure 5. EMULSION MASTER

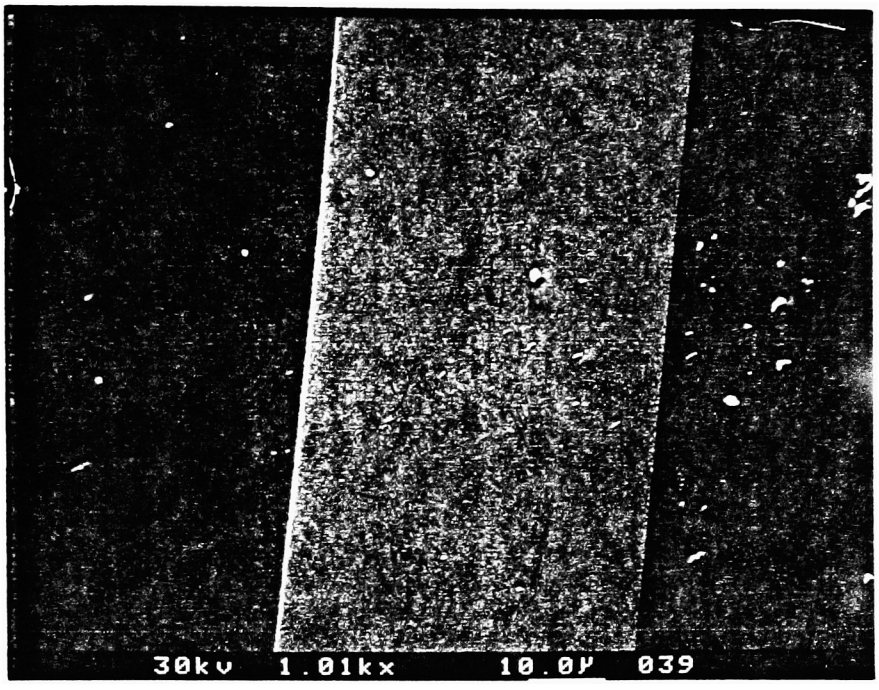

Figure 6. CHROME RETICLE (50 micron line)

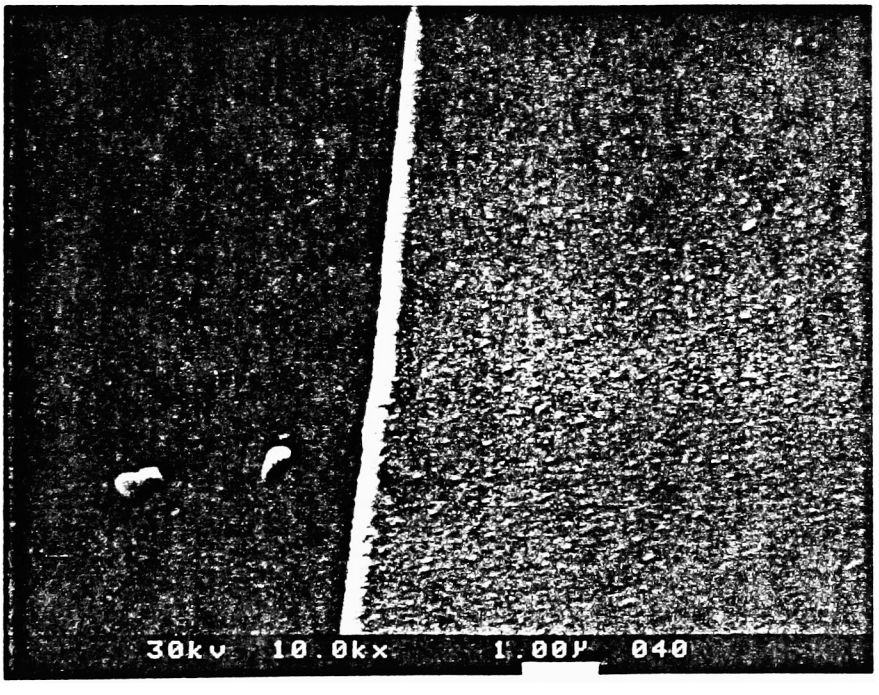

Figure 7. CHROME RETICLE, EDGE (50 micron line)

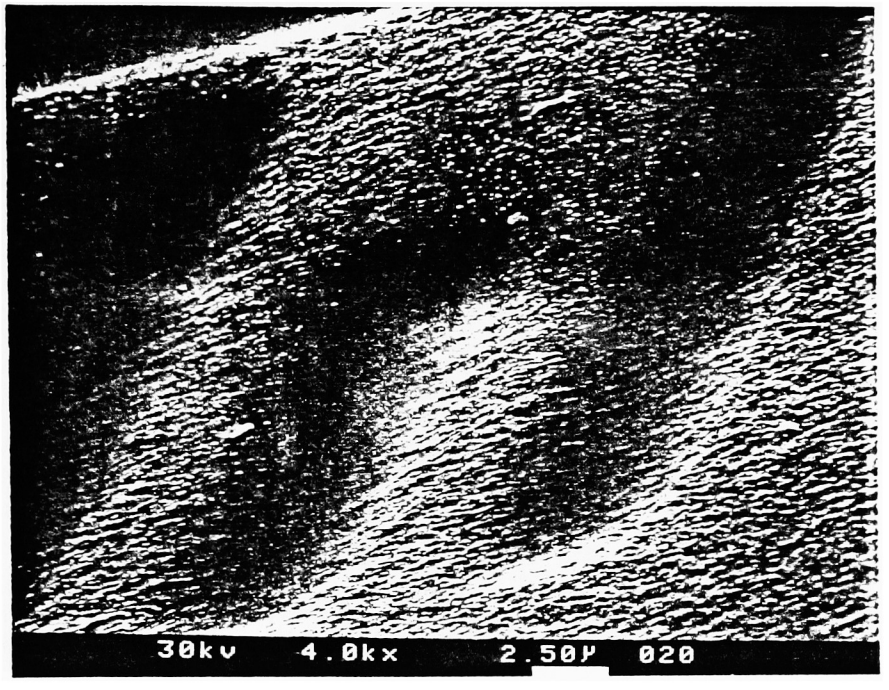

Figure 8. EMULSION CONTACT PRINT

(exposure time = 6 sec.)

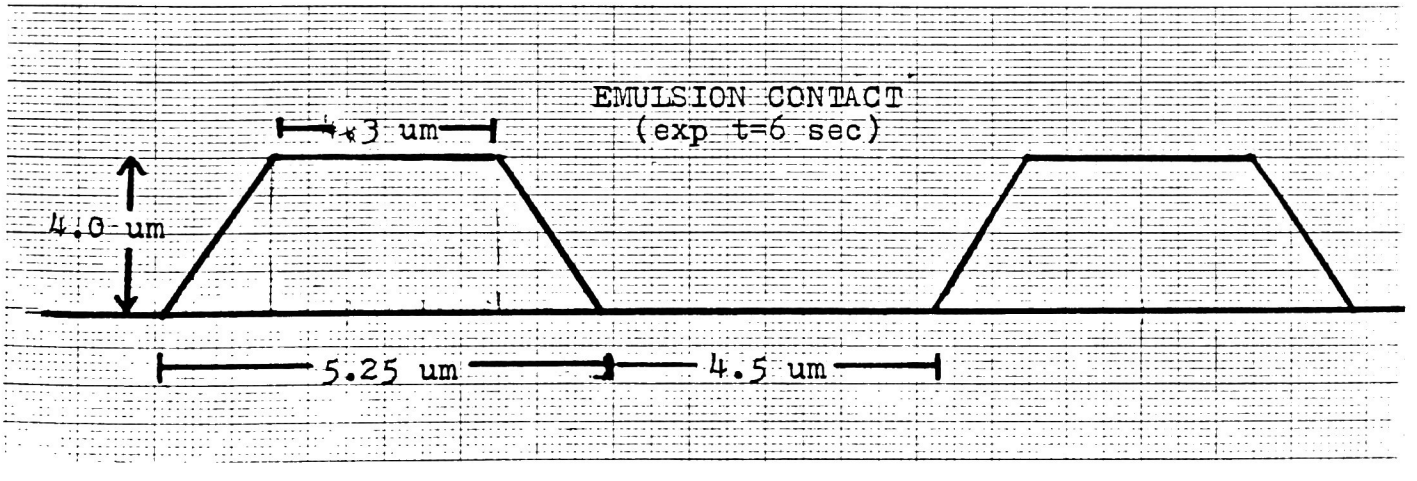

Figure 9. GRAPHICAL DESCRIPTION (of Fig.8)

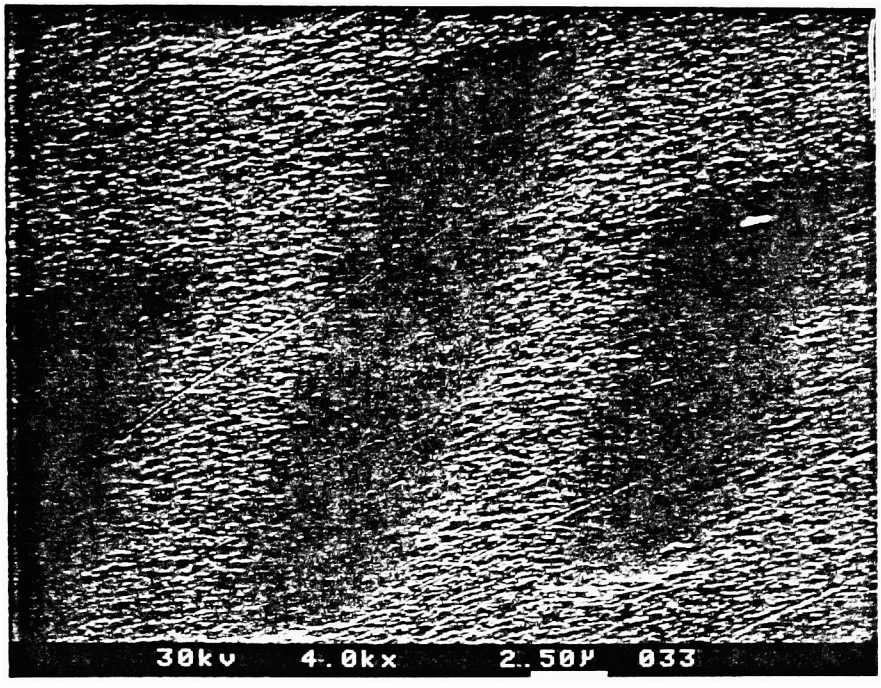

Figure 10. EMULSION CONTACT PRINT

(exposure time = 7 sec.)

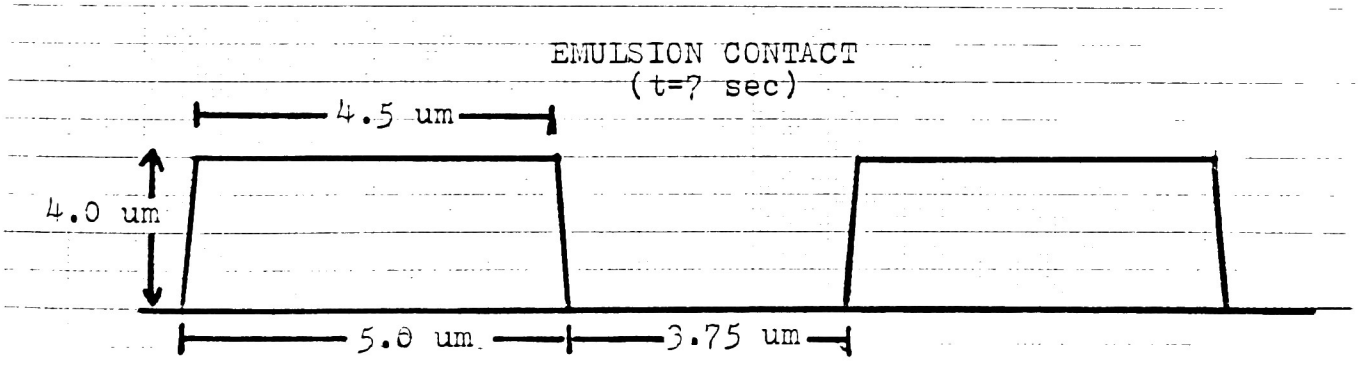

Figure 11. GRAPHICAL DESCRIPTION (of Fig.10)

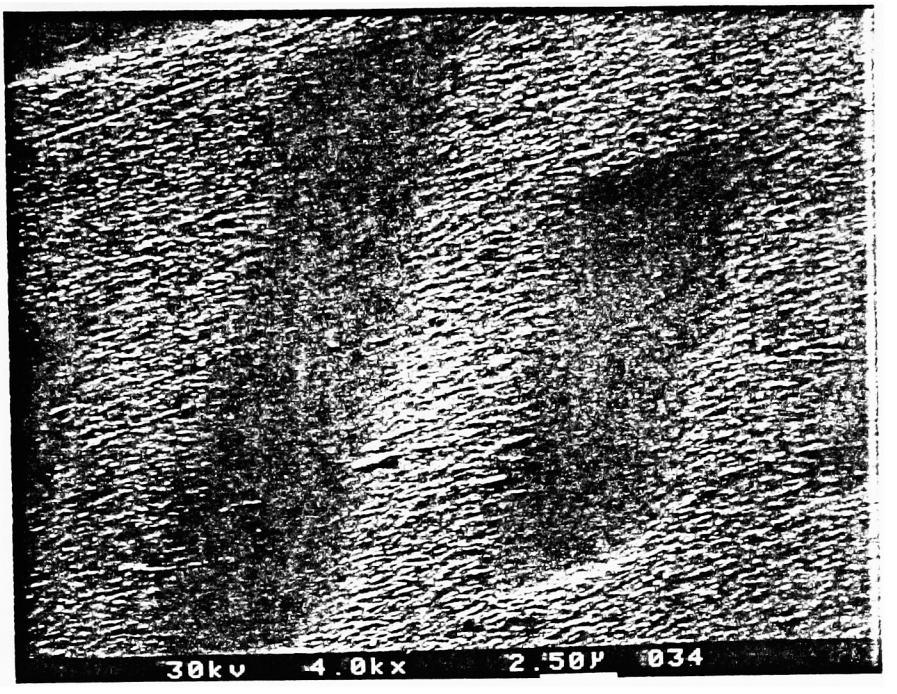

Figure 12. EMULSION CONTACT PRINT

(exposure time = 8 sec.)

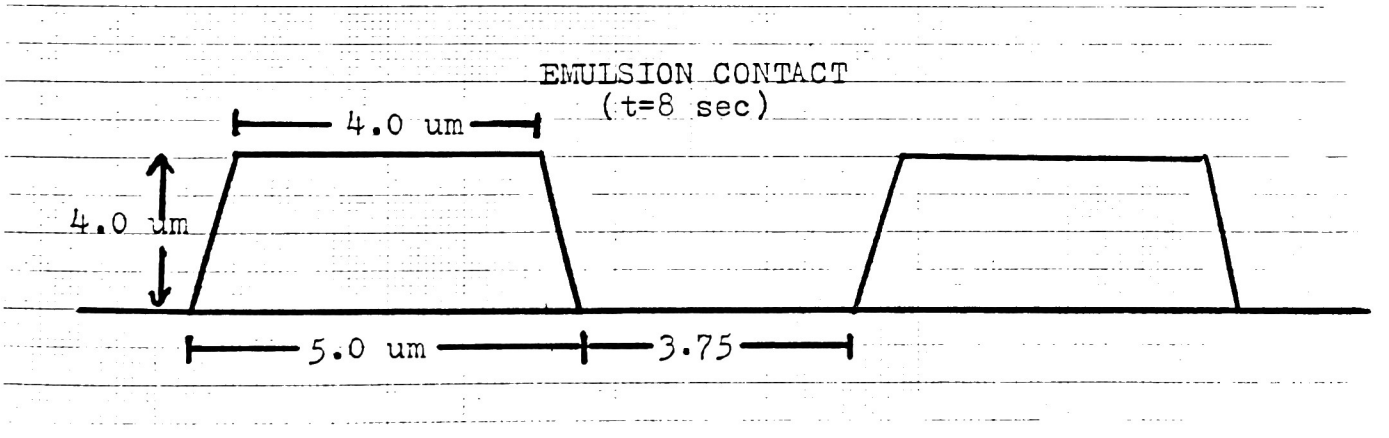

Figure 13. GRAPHICAL DESCRIPTION (of Fig. 12)

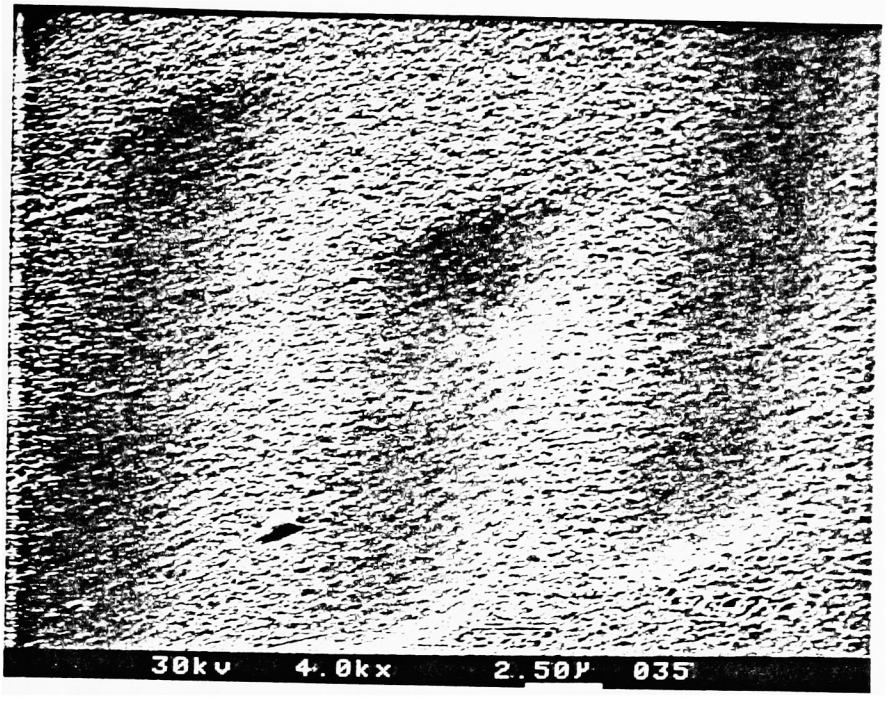

Figure 14. EMULSION CONTACT PRINT

(exposure time = 10 sec.)

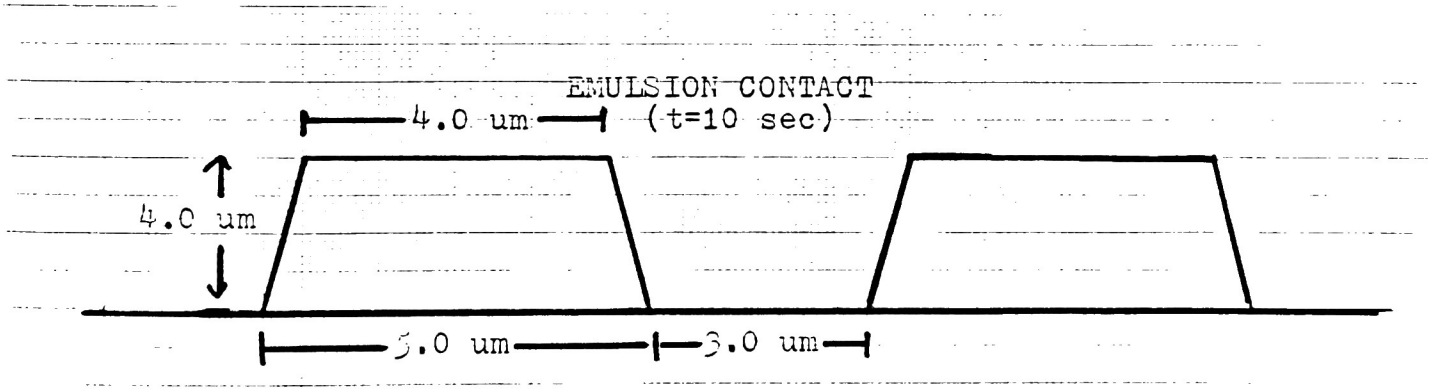

Figure 15. GRAPHICAL DESCRIPTION (of Fig.14)

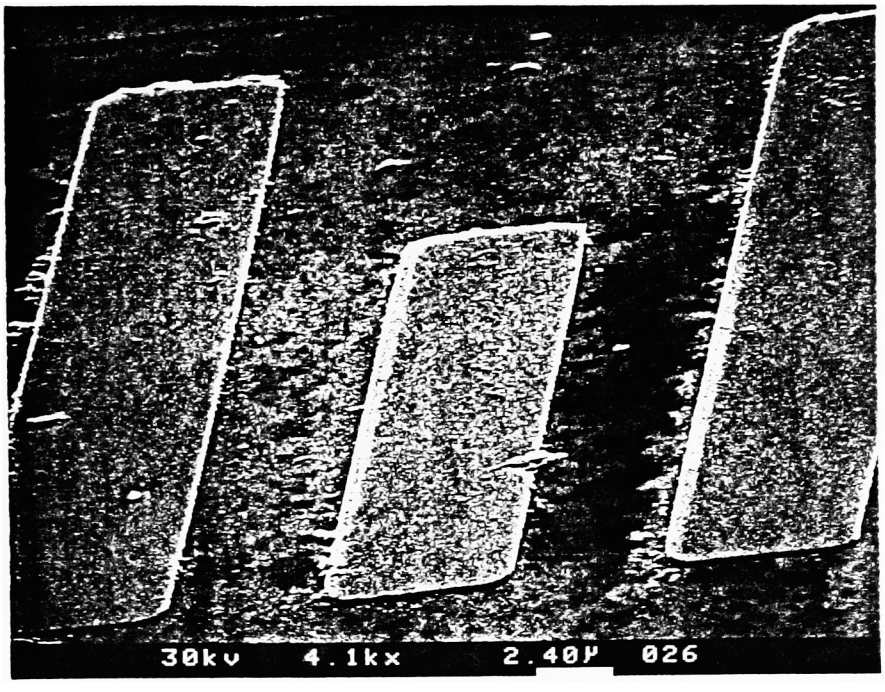

Figure 16. CHROME MASTER

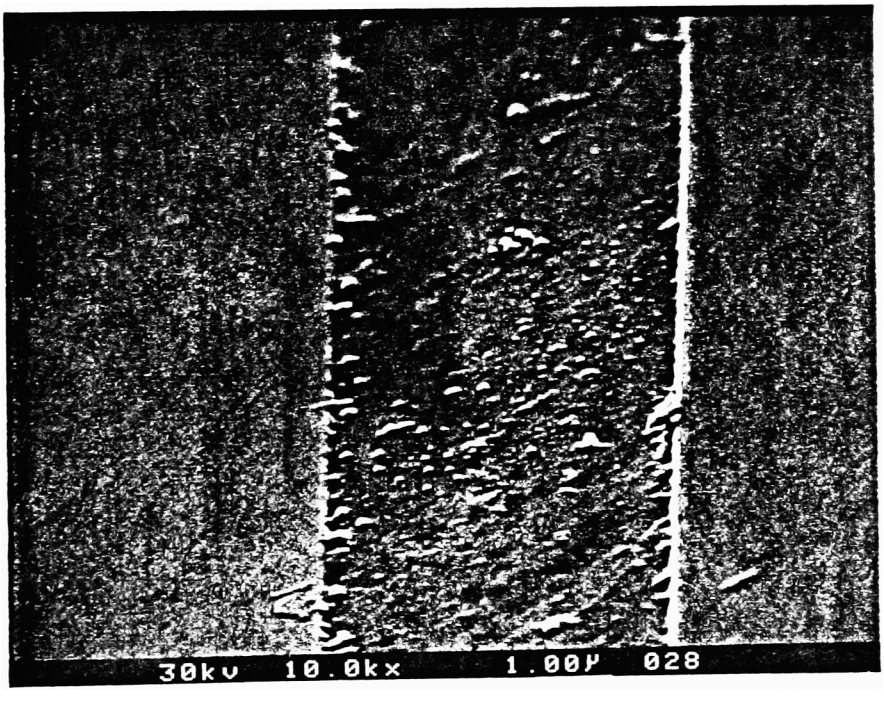

Figure 17. CHROME MASTER (EDGE MAGNIFIED)

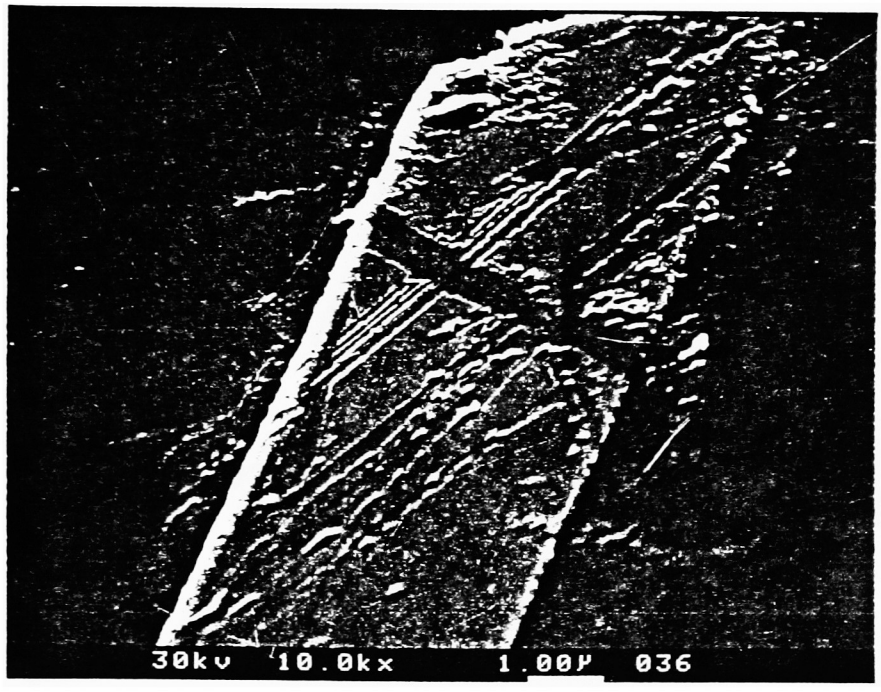

Figure 18. CHROME CONTACT PRINT

(exp. time = 15)

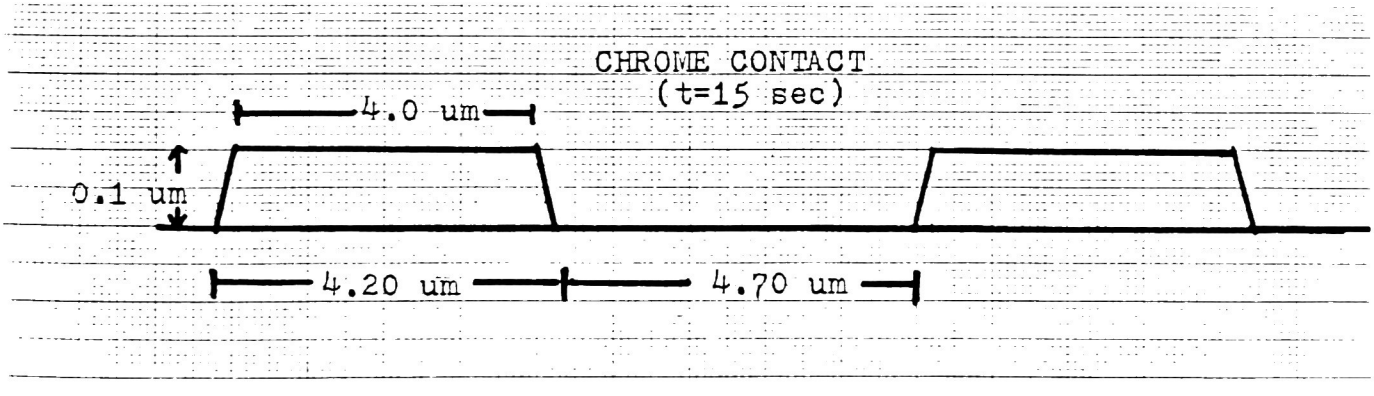

Figure 19. GRAPHICAL DESCRIPTION (of Fig. 18)

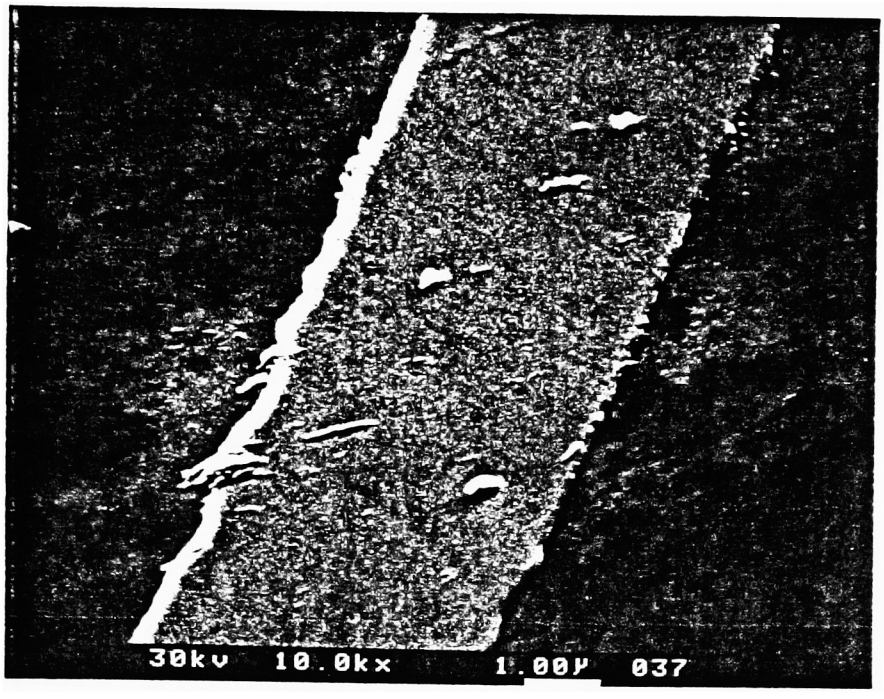

Figure 20. CHROME CONTACT

(exp. time = 12 sec.)

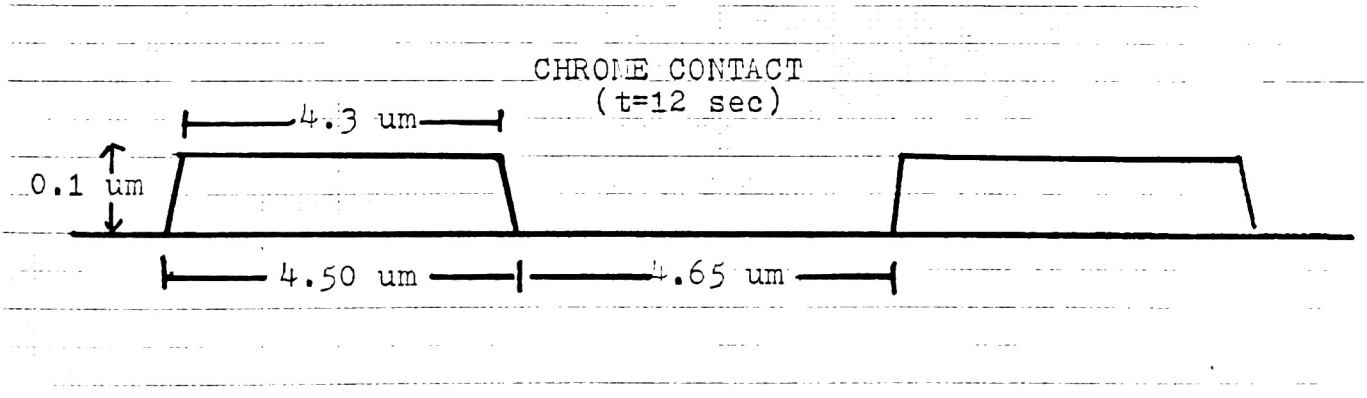

Figure 21. GRAPHICAL DESCRIPTION (of Fig. 20)

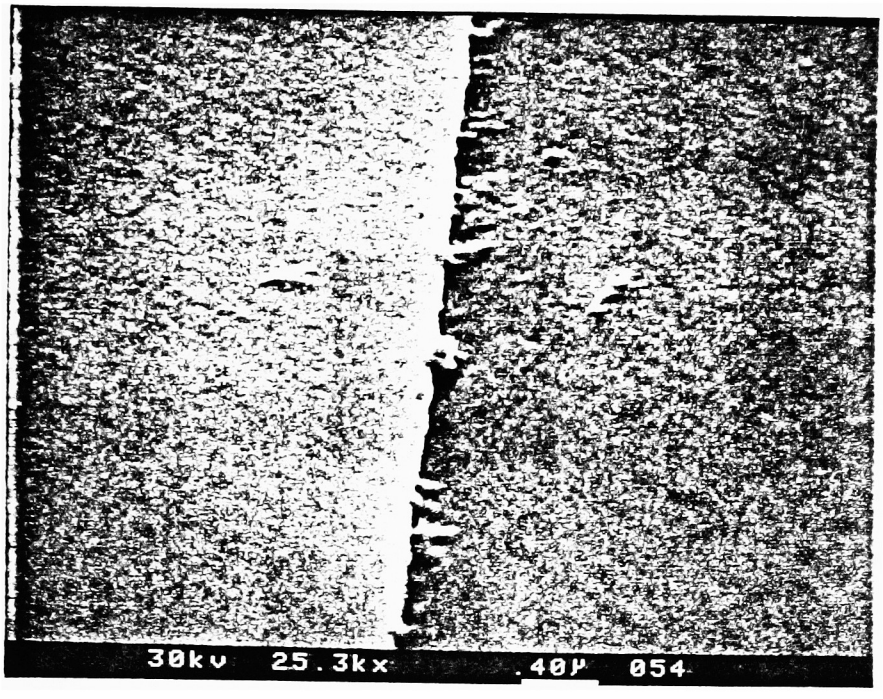

Figure 22. MAGNIFIED EDGE OF CHROME CONTACT

(see fig. 15)

IV. DISCUSSION

Because of the small step heights of the chrome and emulsion images, scanning elecron microscopy (SEM) proved to be a difficult task in evaluating edge gradients. Attempts were made to improve the micrographs by cross sectioning the samples and mounting them on a side. However, the Cambridge SEM in the Microelectronic Engineering Department did not have the resolution capabilities at high magnifications to distinguish 0.1 and 4.0 micron step heights.

Because it was not possible to obtain greater magnification of the edges, a graphical description has been made so that one can compare the different gradients. As a note, these gradients all have been depicted as tapered, but they may also be isotropic, anisotropic, or even undercut. By viewing the emulsion samples it is obvious that these profiles are tapered. The chrome lines exhibit vertical walls as well as a tapered edge.

The micrographs have helped to determine the exposure time for emulsion contact printing. The average linewidth measured optically for the 7 second exposure (fig. 10) was 4.80 +/- 0.427 microns, while measured on the micrograph it was 5.0 microns. Under a microscope, the maximum resolution achieved for the emulsion workplates was 2.5 to 3.0 microns.

Measurements of the chrome lines on the chrome contact

prints did not fall inside the 95% confidence interval placed on the optical measurements. Two measured samples from a micrograph are really no indication of what the population mean is. In terms of resolution, the maximum resolution for the chrome photoplates was 1.8 um. The greater resolution for the mask making process came from using the chrome photoplates and the chemical processing described in the Results section.

Beginning with the chrome reticle (fig. 6,7) which was fabricated by Gould/AMI in a clean room environment, there is virtually no detectable edge gradient. The chrome master (fig. 16, 17) which was made at RIT, possess a gradient of less than 0.1 microns measured laterally. The final chrome contact prints (fig. 18, 20) have an edge gradient of approximately 0.1 micron. There is a considerable amount of degradation along the edges of the chrome lines as one goes from the reticle to the final contact print. What seems to be more of an apparent problem with the chrome contact prints is that there are large protrusions and cuts in the edges of the chrome. These distortions would diffract the incident illumination and would yield uneven exposure on the image plane.

With the emulsion plates, it proved to be difficult to evaluate the lines and spaces using a SEM. Because there are not many topographical changes in the exposed emulsion, it made focusing on the edges very difficult. In fig. 10, the

emulsion contact of t=7 seconds appears to have the steepest slope of all the other emulsion contact prints. With this result and the previously mentioned result of the linewidths on this plate, the process for fabricating an emulsion workplate has been optimized under the constraints of the equipment and conditions used. A non clean room environment, a filar microscope with a +/- 0.5 micron variation in repeatablity, tray processing, chrome sample plates, and SEM analysis were some of the constraints that limited the precision necessary to evaluate submicron gradients.

The graphical descriptions can be used to get an estimate as to how the system performs. Using Tatian's method to determine the MTF, one would sample the edge profile, differentiate it, and fourier transform the line spread function to yield the optical transfer function of the system. Using fig. 11 as an example, the derivative of the edge trace would yield a rectangle spread function (one dimensional analysis). After scaling the spread function to unit area, the modulus of the transform would yield a sinc(f) transfer function. The cutoff frequency would be determined by the sampling interval on the edge. With a change in the edge gradients over such a small distance, the MTF determined would just be equal to the theoretical MTF of the system.

V. CONCLUSION

It was not possible to determine what the MTF was of the total mask making system using the edge gradient technique because of the extremely small edge gradients on the masks. This method of evaluation was limited by the thickness of the chrome (0.1 um) and emulsion (4 um), and also by the SEM analysis. The SEM was able to magnify the edges but depth of focus was sacrificed. Cross-sectioning these small heights only produced images where the gradient was lost in the noise of the edge.

However, it was determined that the edge gradients on these masks would not significantly contribute to the modulation loss in the image. The MTF of the system would be described by the modulation only in the image plane since the modulation of the mask could be assumed one at most frequencies. At smaller linewidths (higher frequencies) on the emulsion mask, there would be a change in modulation because of the changes in density of the smaller emulsion lines. But at these higher frequencies, one is approaching the theoretical resolution capabilities of the optical system in reproducing these linewidths. It can be seen that if a chrome mask was fabricated in the optimum conditions, it would not have any effect on the theoretical MTF of the system.

Further investigation would include using samples with a thicker chrome or emulsion layer, and also to improve the sample preparation for the SEM analysis.

VI. REFERENCES

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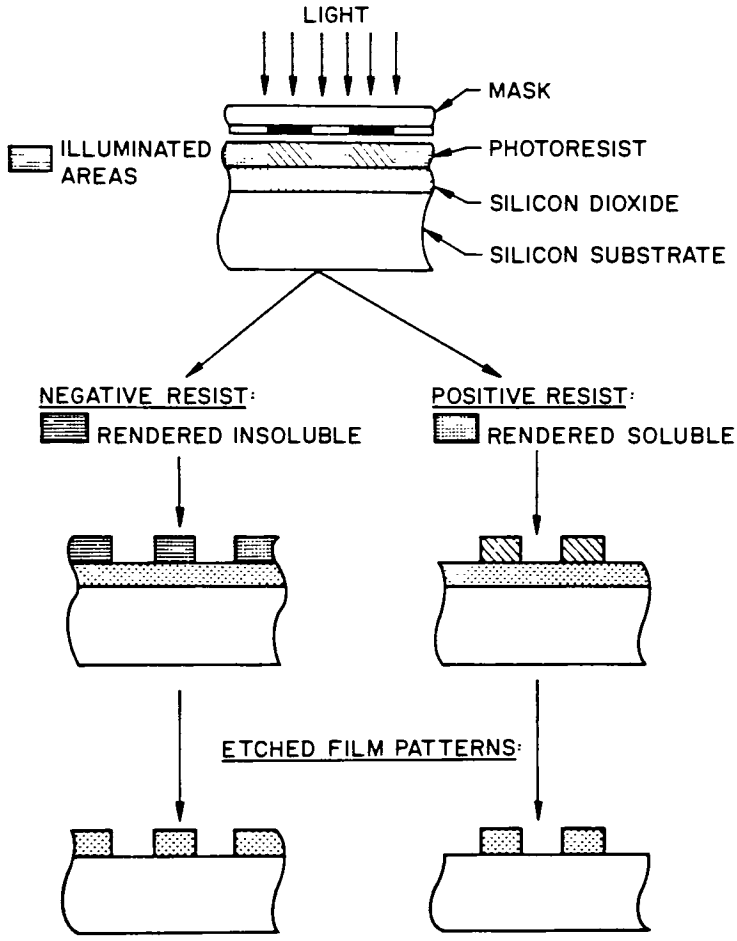
APPENDIX A. MTF PROGRAM

```
C       COMPUTE ODD AND EVEN PARTS OF TRANFER FUNCTION

D       PRINT*, ' '
D       PRINT*, 'F                T1                T2                MODULUS'
D       PRINT*, ' '

        DO FREQUENCY = 1, 20

                F = FREQUENCY*0.1

                SUMEVEN = 0.0
                SUMODD = 0.0

                ARG = 2 * PI * F * EPSILON
                SINC = ( SIN(PI*F*EPSILON) ) / ( PI*F*EPSILON )

                DO N = 1, LIMIT

                        TE =  E2(N) * SIN(N*ARG)
                        TO =  E1(N) * COS(N*ARG)

                        SUMEVEN = SUMEVEN + TE
                        SUMODD = SUMODD + TO

                END DO

                CRCT1 = COS((LIMIT +.5)*ARG)/SINC
                CRCT2 = SIN((LIMIT +.5)*ARG)/SINC

                SUMODD = SUMODD + ( EDGE(MIDDLE) )

                T1(FREQUENCY) = CONSTANT * F * SUMEVEN + CRCT1
                T2(FREQUENCY) = CONSTANT * SUMODD * F - CRCT2

                MODULUS(FREQUENCY) =
     2          SQRT( (T1(FREQUENCY))**2 + (T2(FREQUENCY))**2 )

                FREQ(FREQUENCY) = F

D               PRINT*, FREQ(FREQUENCY), T1(FREQUENCY), T2(FREQUENCY),
     2          MODULUS(FREQUENCY)

        END DO

        RETURN

        END
```

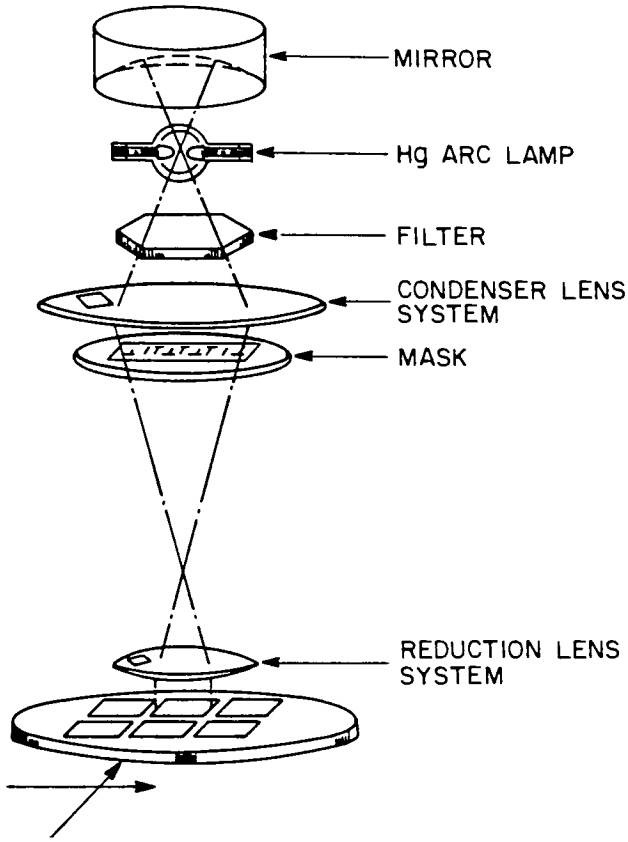
```
      SUBROUTINE TATIAN ( CAPN, EDGE, FREQ, T1, T2, MODULUS )

      REAL  T1(100), T2(100), EDGE(100), E1(100), E2(100), MODULUS(100),
     2  FREQ(100)

      INTEGER  CAPN

      CONSTANTS

      EPSILON = .1
      LIMIT = CAPN / 2
      MIDDLE = LIMIT + 1
      PI = 3.141529
      CONSTANT = 2 * PI * EPSILON

      PRINT*, ' '
      PRINT*, '        N        EDGE(N)'
      PRINT*, ' '

      NORMALIZE EDGE AREA TO UNITY

      EMAX = -100
      EMIN = 100

      DO I = 1, CAPN

              PRINT*, I, EDGE(I)

              IF( EDGE(I) .GT. EMAX ) EMAX = EDGE(I)
              IF( EDGE(I) .LT. EMIN ) EMIN = EDGE(I)

      END DO

      A = EMAX - EMIN
      B = EMIN

      PRINT*, ' '
      PRINT*, '        N        NORMALIZED EDGE(N)'
      PRINT*, ' '

      DO N = 1, CAPN

              EDGE(N) = ( EDGE(N) - B ) / A

              PRINT*, N, EDGE(N)

      END DO

      COMPUTE ODD AND EVEN PARTS OF EDGE TRACE

      PRINT*, ' '
      PRINT*, '        N        EVEN              ODD'
      PRINT*, ' '

      DO N = 1, LIMIT

              E1(N) = ( EDGE(MIDDLE+N) + EDGE(MIDDLE-N) )
              E2(N) = ( EDGE(MIDDLE+N) - EDGE(MIDDLE-N) )

              PRINT*, N, E1(N), E2(N)
```

```
REAL  EDGE(100),MODULUS(100),FREQUENCY(100),ODD(100),EVEN(100)
READ(1,*) N
DO 1 = 1, N
        READ(1,*) EDGE(I)
END DO
CALL TATIAN ( N, EDGE, FREQUENCY, ODD, EVEN, MODULUS )
WRITE(2,*) '20          1'
DO I = 1, 20
        WRITE(2,*) FREQUENCY(I), MODULUS(I)
END DO
END
```

APPENDIX B. GENERAL LITHOGRAPHIC PROCESS



APPENDIX C. SCHEMATIC FOR PHOTOREPEATER



VITA

Marcy E. Levin is currently an undergraduate student in the Imaging and Photographic Science program, at Rochester Institute of Technology, and is anticipating her B.S. degree in May 1985. She was raised in Winthrop, Massachusetts and attended Winthrop High School.

Related work experience includes one summer internship with the Central Intelligence Agency and a second internship with Gould/American Microsystems, Inc., in Santa Clara, CA.

After graduation, she will be employed by General Dynamics, in San Diego, California.